May 30, 1895.

The LORD KELVIN, D.C.L., LL.D., President, in the Chair.

A List of the Presents received was laid on the table, and thanks ordered for them.

In pursuance of notice sent to the Fellows, an election was held to fill the vacancy upon the Council occasioned by the retirement of Professor A. H. Green.

The Statutes relating to the election of the Council and the Statute relating to the election of a Member of Council upon the occurrence of a vacancy were read, and Dr. Armstrong and Mr. R. H. Scott having been, with the consent of the Society, nominated Scrutators, the votes of the Fellows present were taken and the Rev. Thomas George Bonney was declared duly elected.

The following Papers were read:—

I. "On the Temperature Variation of the Thermal Conductivity of Rocks." By LORD KELVIN, P.R.S., and J. R. ERSKINE MURRAY, B.Sc., 1851 Exhibition Scholar. Received May 24, 1895.

§ 1. The experiments described in this communication were undertaken for the purpose of finding temperature variation of thermal conductivity of some of the more important rocks of the earth's crust.

§ 2. The method which we adopted was to measure, by aid of thermoelectric junctions, the temperatures at different points of a flux line in a solid, kept unequally heated by sources (positive and negative) applied to its surface, and maintained uniform for a sufficiently long time to cause the temperature to be as nearly constant at every point as we could arrange for. The shape of the solid and the thermal sources were arranged to cause the flux lines to be, as nearly as possible, parallel straight lines; so that, according to Fourier's elementary theory and definition of thermal conductivity, we should have

$$\frac{k(\mathrm{M}, \mathrm{B})}{k(\mathrm{T}, \mathrm{M})} = \frac{[v(\mathrm{M}) - v(\mathrm{T})] \div \mathrm{MT}}{[v(\mathrm{B}) - v(\mathrm{M})] \div \mathrm{BM}},$$

where T, M, B denote three points in a stream line (respectively next to the top, at the middle, and next to the bottom in the slabs and columns which we used); $v(\mathrm{T})$, $v(\mathrm{M})$, $v(\mathrm{B})$ denote the steady tem-

peratures at these points; and $k(\mathrm{T}, \mathrm{M})$, $k(\mathrm{M}, \mathrm{B})$, the mean conductivities between T and M, and between M and B respectively.

§ 3. The rock experimented on in each case consisted of two equal and similar rectangular pieces, pressed with similar faces together. In one of these faces three straight parallel grooves are cut, just deep enough to allow the thermoelectric wires and junctions to be embedded in them, and no wider than to admit the wires and junctions (see diagram, § 8 below). Thus, when the two pieces of rock are pressed together, and when heat is so applied that the flux lines are parallel to the faces of the two parts, we had the same result, so far as thermal conduction is concerned, as if we had taken a single slab of the same size as the two together, with long fine perforations to receive the electric junctions. The compound slab was placed with the perforations horizontal, and their plane vertical. Its lower side, when thus placed, was immersed under a bath of tin, kept melted by a lamp below it. Its upper side was flooded over with mercury in our later experiments (§§ 6, 7, 8), as in Hopkins' experiments on the thermal conductivity of rock. Heat was carried off from the mercury by a measured quantity of cold water poured upon it once a minute, allowed to remain till the end of a minute, and then drawn off and immediately replaced by another equal quantity of cold water. The chief difficulty in respect to steadiness of temperature was the keeping of the gas lamp below the bath of melted tin uniform. If more experiments are to be made on the same plan, whether for rocks or metals, or other solids, it will, no doubt, be advisable to use an automatically regulated gas flame, keeping the temperature of the hot bath in which the lower face of the slab or column is immersed at as nearly constant a temperature as possible, and to arrange for a perfectly steady flow of cold water to carry away heat from the upper surface of the mercury resting on the upper side of the slab or column. It will also be advisable to avoid the complication of having the slab or column in two parts, when the material and the dimensions of the solid allow fine perforations to be bored through it, instead of the grooves which we found more readily made with the appliances available to us.

§ 4. Our first experiments were made on a slate slab, 25 cm. square and 5 cm. thick, in two halves, pressed together, each 25 cm. by 12·5, and 5 cm. thick. One of these parts cracked with a loud noise in an early experiment, with the lower face of the composite square resting on an iron plate heated by a powerful gas burner, and the upper face kept cool by ice in a metal vessel resting upon it. The experiment indicated, very decidedly, less conductivity in the hotter part below the middle than in the cooler part above the middle of the composite square slab. We supposed this might possibly be due to the crack, which we found to be horizontal and below the middle,

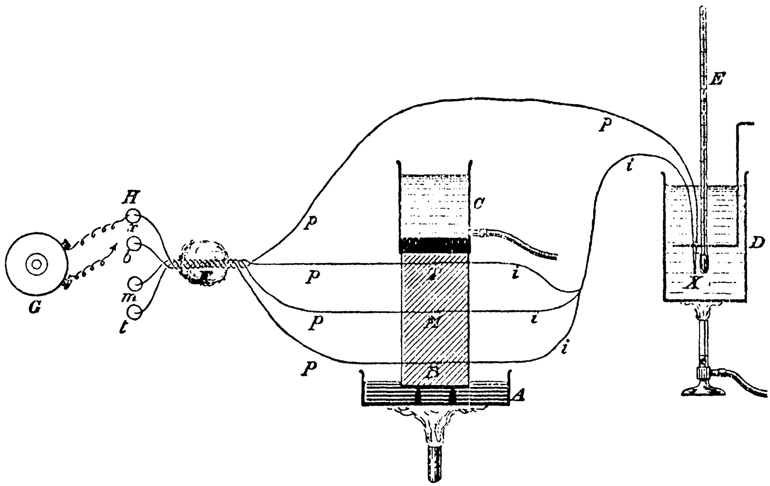
and to be complete across the whole area of $12\frac{1}{2}$ cm. by 5, across which the heat was conducted in that part of the composite slab ; and to give rise to palpably imperfect fitting together of the solid above and below it. We therefore repeated the experiment with the composite slab turned upside down, so as to bring the crack in one half of it now to be above the middle, instead of below the middle, as at first. We still found for the composite slab less conductivity in the hot part below the middle than in the cool part above the middle. We inferred that, in respect to thermal conduction through slate across the natural cleavage planes, the thermal conductivity diminishes with increase of temperature.

§ 5. We next tried a composite square slab of sandstone of the same dimensions as the slate, and we found for it also decisive proof of diminution of thermal conductivity with increase of temperature. We were not troubled by any cracking of the sandstone, with its upper side kept cool by an ice-cold metal plate resting on it, and its lower side heated to probably as much as 300° or 400° C.

§ 6. After that we made a composite piece, of two small slate columns, each 3·5 cm. square and 6·2 cm. high, with natural cleavage planes vertical, pressed together with thermoelectric junctions as before; but with appliances (§ 10 below) for preventing loss or gain of heat across the vertical sides, which the smaller horizontal dimensions (7 cm., 3·5 cm.) might require, but which were manifestly unnecessary with the larger horizontal dimensions (25 cm., 25 cm.) of the slabs of slate and sandstone used in our former experiments. The thermal flux lines in the former experiments on slate were perpendicular to the natural cleavage planes, but now, with the thermal flux lines parallel to the cleavage planes, we still find the same result, smaller thermal conductivity at the higher temperatures. Numerical results will be stated in § 12 below.

§ 7. Our last experiments were made on a composite piece of Aberdeen granite, made up of two columns, each 6 cm. high and 7·6 cm. square, pressed together, with appliances similar to those described in § 6 ; and, as in all our previous experiments on slate and sandstone, we found less thermal conductivity at higher temperatures. The numerical results will be given in § 12 below.

§ 8. The accompanying diagram represents the thermal appliances and thermoelectric arrangement of §§ 6, 7. The columns of slate or granite were placed on supports in a bath of melted tin with about 0·2 cm. of their lower ends immersed. The top of each column was kept cool by mercury, and water changed once a minute, as described in § 3 above, contained in a tank having the top of the stone column for its bottom and completed by four vertical metal walls fitted into grooves in the stone and made tight against wet mercury by marine glue.



Iron wires are marked *i*.
Platinoid wires are marked *p*.
B, M, T. Thermoelectric junctions in slab.
X. " " oil bath.
A. Bath of molten tin.
C. Tank of cold water.
D. Oil bath.
E. Thermometer.
F. Junctions of platinoid and copper wires. The wires are insulated from one another, and wrapt all together in cotton wool at this part, to secure equality of temperature between these four junctions, in order that the current through the galvanometer shall depend solely on differences of temperature between whatever two of the four junctions, X, T, M, B, is put in circuit with the galvanometer.
G. Galvanometer.
H. Four mercury cups, for convenience in connecting the galvanometer to any pair of thermoelectric junctions.
x, *b*, *m*, *t*, are connected, through copper and platinoid, with X, B, M, T, respectively.

§ 9. The temperatures, v(B), v(M), v(T) of B, M, T, the hot, intermediate, and cool points in the stone, were determined by equalising to them successively the temperature of the mercury thermometer placed in the oil-tank, by aid of thermoelectric circuits and a galvanometer used to test equality of temperature by nullity of current through its coil when placed in the proper circuit, all as shown in the diagram. The steadiness of temperature in the stone was tested by keeping the temperature of the thermometer constant, and observing the galvanometer reading for current when the junction in the oil-tank and one or other of the three junctions in the stone were placed in circuit. We also helped ourselves to attaining constancy of

temperature in the stone by observing the current through the galvanometer, due to differences of temperature between any two of the three junctions B, M, T placed in circuit with it.

§ 10. We made many experiments to test what appliances might be necessary to secure against gain or loss of heat by the stone across its vertical faces, and found that *kieselguhr*, loosely packed round the columns and contained by a metal case surrounding them at a distance of 2 cm. or 3 cm., prevented any appreciable disturbance due to this cause. This allowed us to feel sure that the thermal flux lines through the stone were very approximately parallel straight lines on all sides of the central line BMT.

§ 11. The thermometer which we used was one of Cassella's (No. 64,168) with Kew certificate (No. 48,471) for temperature from 0° to 100°, and for equality in volume of the divisions above 100°. We standardised it by comparison with the constant volume air thermometer* of Dr. Bottomley with the following result. This is satisfactory as showing that when the zero error is corrected the greatest error of the mercury thermometer, which is at 211° C., is only 0·3°.

Reading.		Correction to be subtracted from reading of mercury thermometer.
Air thermometer.	Mercury thermometer.	
0°	1°·9	1·9
120·2	122·2	2·0
166·8	168·6	1·8
211·1	212·7	1·6
265·7	267·5	1·8

§ 12. Each experiment on the slate and granite columns lasted about two hours from the first application of heat and cold; and we generally found that after the first hour we could keep the temperatures of the three junctions very nearly constant. Choosing a time of best constancy in our experiments on each of the two substances, slate and granite, we found the following results:—

Slate: flux lines parallel to cleavage.

$$v(\mathrm{T}) = 50^\circ{\cdot}2\ \mathrm{C}.$$

$$v(\mathrm{M}) = 123^\circ{\cdot}3.$$

$$v(\mathrm{B}) = 202^\circ{\cdot}3.$$

* 'Phil. Mag.,' August, 1888, and 'Edinb. Roy. Soc. Proc.,' January 6, 1888.

The distances between the junctions were BM = 2·57 cm. and MT = 2·6 cm. Hence by the formula of § 2,

$$\frac{k(\mathrm{M, B})}{k(\mathrm{T, M})} = \frac{73·1 \div 2·6}{79·0 \div 2·57} = \frac{28·1}{30·7} = 0·91.$$

Aberdeen granite:

$$v(\mathrm{T}) = 81^{\circ}·1.$$
$$v(\mathrm{M}) = 145^{\circ}·6.$$
$$v(\mathrm{B}) = 214^{\circ}·6.$$

The distances between the junctions were BM = 1·9 cm. and MT = 2·0 cm.

$$\frac{k(\mathrm{MB})}{k(\mathrm{TM})} = \frac{64·5 \div 2·0}{69·0 \div 1·9} = \frac{32·2}{36·3} = 0·88.$$

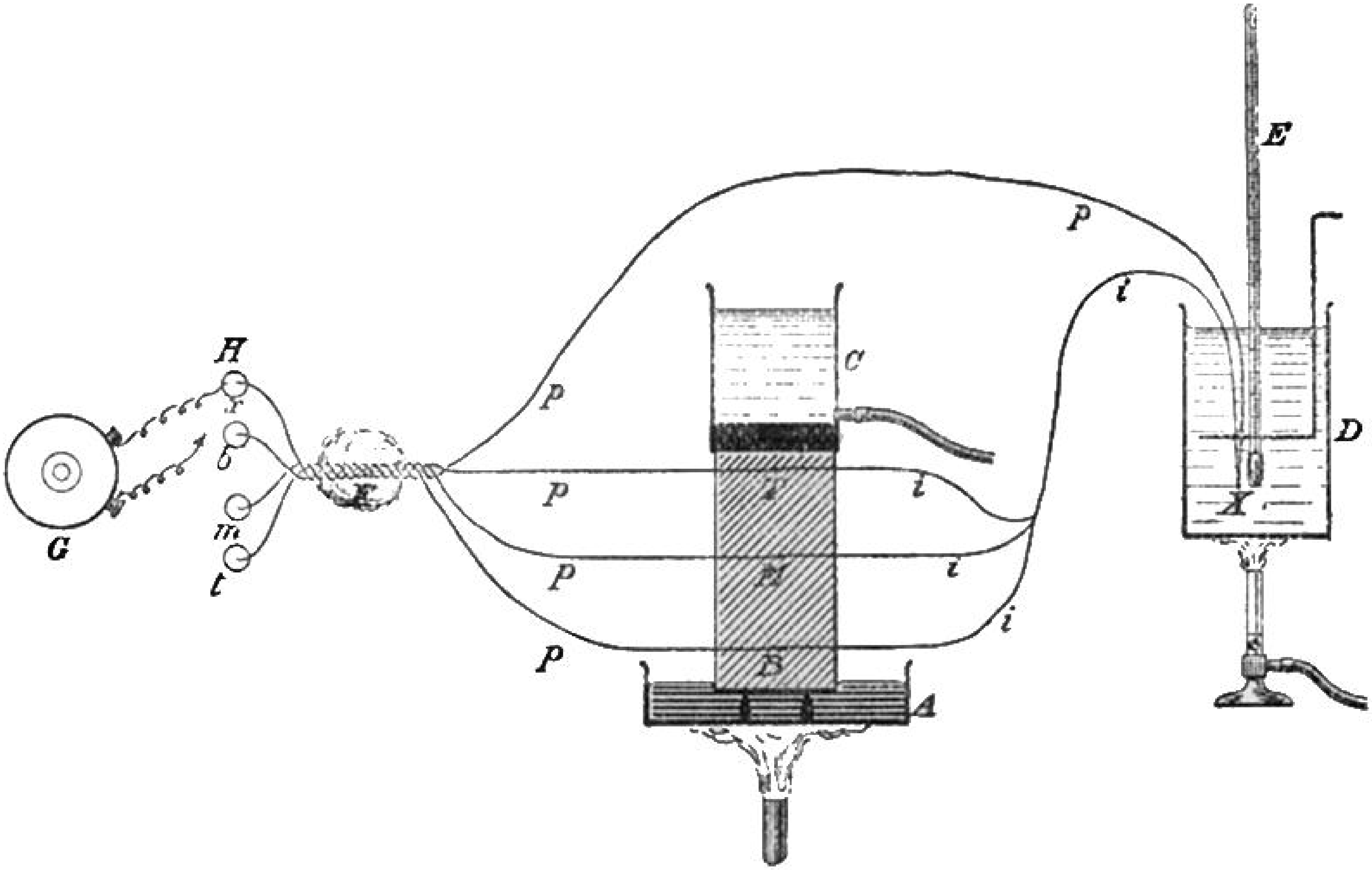
§ 13. Thus we see, that for slate, with lines of flux parallel to cleavage planes, the mean conductivity in the range from 123° C. to 202° C. is 91 per cent. of the mean conductivity in the range from 50° C. to 123° C., and for granite, the mean conductivity in the range from 145° C. to 214° C. is 88 per cent. of the mean conductivity in the range from 81° C. to 145° C. The general plan of apparatus, described above, which we have used only for comparing the conductivities at different temperatures, will, we believe, be found readily applicable to the determination of conductivities in absolute measure.

II. "The Kinematics of Machines." By T. A. HEARSON, M.Inst.C.E., Professor of Mechanism and Hydraulic Engineering, Royal Indian Engineering College, Coopers Hill. Communicated by Professor COTTERILL, F.R.S. Received March 19, 1895.

(Abstract.)

In this paper the author regards a machine as an embodiment of a movement. The method of construction and the proportions of the parts are not taken into consideration, except so far as may be necessary to explain the conditions requisite for the kinds of motions with which they are supposed to be endowed. All other considerations relating to form and proportion are omitted, as belonging to the subject of machine design. Neither does the author take account of the forces which actuate and oppose the movement of the machine, such matters belonging to the subject Dynamics of Machines.

The object of the paper is to analyse the movements only, and to



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F. Junctions of platinoid and copper wires. The wires are insulated from one another, and wrapt all together in cotton wool at this part, to secure equality of temperature between these four junctions, in order that the current through the galvanometer shall depend solely on differences of temperature between whatever two of the four junctions, X, T, M, B, is put in circuit with the galvanometer.

G. Galvanometer.

H. Four mercury cups, for convenience in connecting the galvanometer to any pair of thermoelectric junctions.

x, b, m, t, are connected, through copper and platinoid, with X, B, M, T, respectively.